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PREFERRED AIR VELOCITY AND LOCAL COOLING EFFECT OF DESK FANS IN WARM ENVIRONMENTS

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ABSTRACT

Common experiences, standards, and laboratory studies show that increased air velocity helps to offset warm sensation due to high environmental temperatures. In warm climate regions the opening of windows and the use of desk or ceiling fans are the most common systems to generate increased airflows to compensate for higher environmental temperatures at the expense of no or relatively low energy consumption.

When using desk fans, local air movement is generated around the occupant and a certain cooling effect is perceived. The impact of the local air movement generated by different air flow patterns, and the possibility to keep comfortable conditions for the occupants in warm environments were evaluated in studies with human subjects.

In an office-like climatic chamber, the effect of higher air velocity was investigated at room temperatures between 26°C to 34°C and at constant absolute humidity of 12.2 g/kg. By a thermal manikin the effect of direct air movement generated by a personal desk fan at 26 °C, 28 °C, or 30 °C room temperatures and the achievable thermal comfort was also analyzed.

Results show that it is possible to offset warm sensation within a range of indoor conditions using increased air velocity. Besides, higher air velocities and personal control increase the acceptability of the indoor environment at higher air temperatures with a limited energy consumption compared to full air conditioning during summer seasons in warmer countries. Comparing the study with Danish subjects with previous findings with Chinese subjects showed that subjects used to warmer climate could accept higher air velocities and felt less uncomfortable.

KEYWORDS

Thermal comfort, air velocity, personal control, desk fan

1 INTRODUCTION

Thermal comfort Standards ISO 7730-2005, ISO 15251/2007 and ASHRAE 55-2010, for indoor environments include air movement limits that protect the occupants of being exposed to draught problems and discomfort. The limits of air movement are dependent on air turbulence (Tu) and frequencies, while the direction is not considered.

Fanger and Pedersen (1977) and Zhou et al. (2002) demonstrated that the impact on human sensation of draught is higher at frequencies between 0.2-0.6 Hz, while it is not significant at frequencies below 0.1 Hz, as well reported in Tanabe and Kimura (1994) study, and at frequencies higher of 1 Hz.

When considering the direction, Fanger et al. (1974) demonstrated by the human subjects experiment for seated occupants that there is no influence of the direction of air flow on

creating thermal comfort even though the heat loss measured by the thermal manikin was higher when the air motion was from front. Later, Zhou (1999) in a similar experiment found that the draught rating (DR) reported at 26 °C was lower from the front airflow movement and the reason could be due to a weaker natural convection in front of a seated person which has a thicker boundary layer in front than at the back (Homma and Yakiyama, 1988). Therefore subjects may naturally prefer the airflow from the front that often occurs in the daily life when walking, cycling, etc.

Many previous laboratory and field studies (Rohles et al. 1974, Tanabe and Kimura 1989, Scheatzle et al. 1989, Fountain 1991, Fountain et al. 1994, Mayer 1992, Arens et al. 1998, Zhang et al. 2007, Zhou et al. 2006, Cândido et al. 2010, Cattarin et al. 2012) have demonstrated that higher air movement can compensate for warmer temperatures in make people more comfortable.

The ISO Standard 7730-2005 and ASHRAE Standard 55-2010 adopted a model that provide a conservative upper limit for air velocity that protects occupants who are sensitive to air movement, occupants who feel cooler than neutral, or occupants who are occupied mostly with sedentary work.

In Standard ISO 7730-2005 it is also recognized that: “People used to working and living in warm climates can more easily accept and maintain a higher work performance in hot environments than those living in colder climates.” For that reason, as numerous studies show, in warm environments people seem to be less sensitive to draught than the predicted by DR model and as consequences higher air velocity could be used for obtaining neutral environment at higher temperatures.

In Naturally Ventilated buildings (NV) during summer time there was no sensation of draught and 80.6% of people wanted more air movement (Yang and Zhang, 2009) increasing to 90% and 96% in Baizhan et al. (2010) and Zhang et al. (2007) studies. Besides, those last two studies observed that the demand for less air movement under cool sensation is much smaller (30%) than the overwhelming demand for more air movement at warm sensation (80%).

The increase of air velocity can be achieved by windows opening, ceiling or free standing fans (including desk fan) at the expense of no or relatively low energy consumption (Koranteg and Mahdavi 2011, Aynsley 2007, Yamtraipat et al. 2006, Schiavon and Melikov 2009, Sun et al. 2013).

It is known that those solutions are often used in NV buildings in warm countries, like in the Mediterranean, Asian, or South America, where the people are used to natural ventilation systems and they can easily adapt and accept environments with air temperatures up to 28 °C (Cândido et al. 2012, Kubo et al. 1997, Zhang et al. 2010, Feriadi and Wong 2004).

Today higher level of air velocities are allowed in ASHRAE Standard 55 (2010) but only under personal control of the occupants. Feriadi and Wong (2004) reported that the occupant control focusing on preferred air velocity can provide a higher percentage of people satisfied while Boerstra et al. (2013) found a significant positive correlation with overall comfort in summer and perceived air quality when control on ventilation is allowed.

Perception of control, behavioural actions and human expectation studies (Feriadi and Wong 2004, Weiwei et al. 2012), mainly referring to warm environments acceptability, reported the increase of fan usage for cooling with the increase of temperature.

The adaptation at warmer room temperature with the use of the desk fans as support for cooling, with the perspective of lower energy consumption, was investigated in this study. In particular, the evaluation of comfortable and acceptable environment for the occupants was studied when increased local air velocity and/or preferred air velocity was provided.

In this paper, some results of human subject study are presented. The preferred air velocities at different room temperatures and their capability to offset warm sensation and to provide comfortable and acceptable environment for Scandinavians are presented.

2 METHOD

The experiment was carried out in a climatic chamber that reproduces a typical office room with dimensions $5.9 \times 5.8 \times 3.2 \text{ m}^3$, located at the International Centre for Indoor Environment and Energy, Technical University of Denmark (ICIEE-DTU). The same chamber with similar setup of Cattarin (2012) study was used, providing occupants with a view on the outdoors garden. The office had eight workplaces, each workplace having a desk, office chair, desk lamp, desk fan, and laptop. A partition between the right and left side was located in the middle of the room in order to avoid any influence at the back of each occupant due to the air movement generated by the desk fan of another person (see Figure 1).

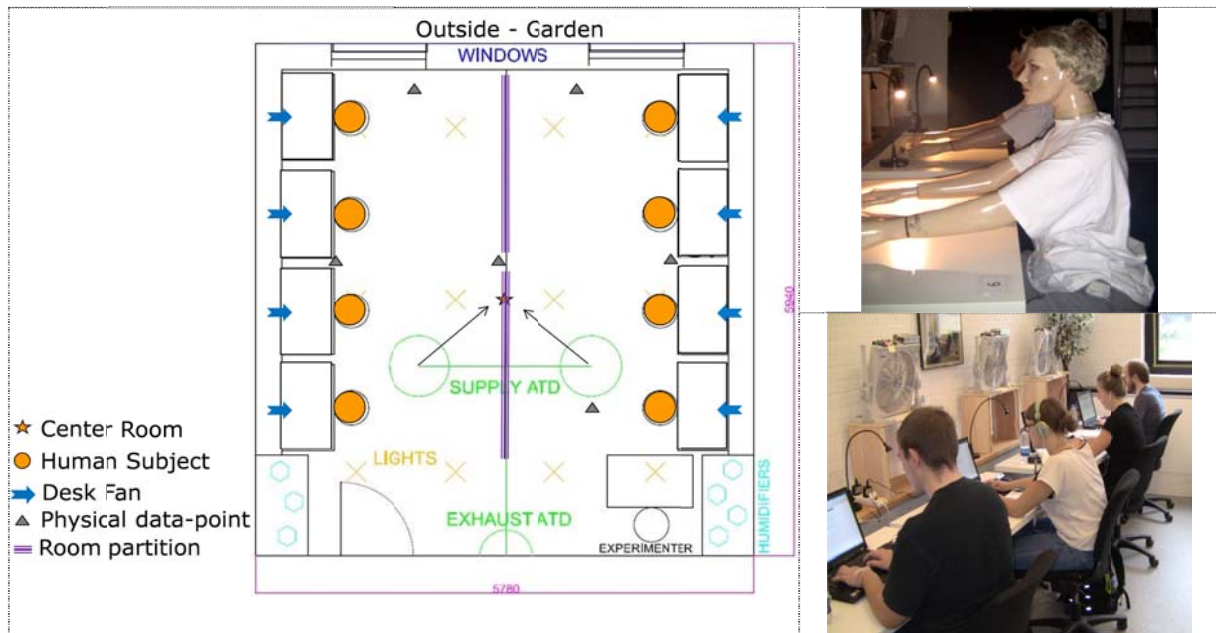


Figure 1: Sketch and setup of the experimental chamber (left) and view of workplace with thermal manikins (right-up) and participants (right-down)

Air and globe temperature sensors, developed at the ICIEE-DTU according Simone et al. (2007) with an accuracy of $\pm 0.3 \text{ }^{\circ}\text{C}$, omnidirectional anemometers with accuracy of $\pm 0.05 \text{ m/s}$ and HOBO humidity sensors with accuracy of $\pm 5\%$ were used during the experiments to record the physical parameters in different locations of the room (see Figure 1) and at different heights above the floor (mainly at 0.1, 0.6, 1.1 m and 1.7 m).

Skin temperatures of the occupants were recorded by iButtons sensors (as suggested by van Marken Lichtenbelt et al. 2006, and Smith et al. 2010). Particular the forehead was measured in order to estimate the local cooling effect generated by the fan. Four points schema suggested by the Standard ISO 9886 (2003) was used for estimating the average body skin temperature.

During the experimental session, working tasks were given to the participants so that an activity level of 1.2 met could be maintained. The type of clothes worn by the occupants resulted in a clothing insulation of 0.5-0.6 clo-value. A ventilation system was used to provide fresh air and keep a room background air velocity of 0.15-0.18 m/s just below the suggested limit in ISO 7730 (2005). Air humidity and operative temperature were controlled by the main conditioning system in order to provide the required values for the different experimental environments that were investigated.

The absolute humidity was kept constant at 12.2 g/kg and room temperature of $26 \text{ }^{\circ}\text{C}$, $28 \text{ }^{\circ}\text{C}$, $30 \text{ }^{\circ}\text{C}$, $32 \text{ }^{\circ}\text{C}$ and $34 \text{ }^{\circ}\text{C}$ were investigated.

At the room temperature conditions of 26 °C, 28 °C and 30 °C, two thermal manikins were used to evaluate the cooling effect provided by the higher constant air velocity. They have been placed at the desks in the same experimental room (see Figure 1) exposed to the investigated conditions. Body parts equivalent temperatures and heat losses were recorded. Based on those data the acceptability of the thermal environment was estimated together with the PMV index and by the human occupants' responses.

A total of 27 Danes participated in the experiments. Their average anthropometric data is reported in Table 1. The participants spent 15 minutes in the pre-test room at low activity level. The exposure to the warm environmental conditions lasted 2 hours for each room temperature settings.

Table 1. Anthropometric data of participants attending the study

Sex	No. of subjects	Age (years)	Height (cm)	Weight (kg)	Du Bois area (m ²)	Body Mass Index (BMI)
females	11	22 ± 5	167 ± 13	59 ± 11	1.66 ± 0.15	21.4 ± 4.7
males	16	24 ± 9	178 ± 9	72 ± 24	1.89 ± 0.22	22.9 ± 8.4
females + males	27	23 ± 10	173 ± 19	66 ± 30	1.78 ± 0.33	22.1 ± 9.2

As shown in Figure 2, the occupants had a period in which they could adapt to the heat followed by the local exposure of 15 minutes at the constant air flow, provided by the desk fans in direction to the face. The air speed settings of the fans, at constant air flow, were random.

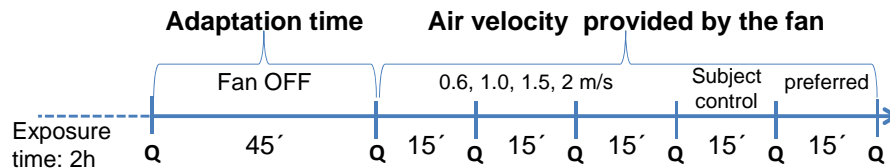


Figure 2: Time Schedule of the Experiments

The used desk fan, see Figure 1, is a prototype of fan developed at Tsinghua University in China, which can generate different type of air flow, at very high air velocity and different turbulent intensity, as explained in Zhou et al. (2006). In this experiment, aimed for evaluating the cooling impact on the occupant, the turbulence intensity of 22% of the constant air flow, at sample frequency of 10 Hz, was measured at the face location of the participants. In addition the participants, after one hour and thirty minutes in the experimental chamber, could regulate the air velocity by using a dimmer switch that provides a continuous variation of the air speed. Along the experiment, at each change (see Figure 2), the subjects were asked to fill in the provided questionnaires (Q) giving us information regarding: thermal environment (thermal comfort, thermal acceptability, air movement preference, etc.), air quality (perception of air quality, air humidity, etc.), experienced sick building symptoms (dry eyes, irritated throat and nose irritation, etc.), and etc.

3 RESULTS AND DISCUSSIONS

The dry heat losses of the thermal manikin at steady-state conditions were measured when the airflow generated by the fan was at 0 m/s, 0.6 m/s, 1 m/s, and 1.5 m/s of constant air velocities in direction of the occupant face (80 cm perpendicular distance at 1.2 m above the floor) and at three investigated room temperatures of 26 °C, 28 °C, and 30 °C (see Figure 3a and 3b). Average values of the equivalent temperatures and dry heat loss of the whole body and the head are reported in Table 2, where the heat loss at the head region was calculated as an average of the heat loss from the neck, face and crown. Thus, the influence of the airflow

direction is diminished. The heat transfer coefficient (dry heat loss) for the head was approximately $4.5 \text{ W/m}^2\text{K}$, while for the face $5.6 \text{ W/m}^2\text{K}$ which is similar to values measured by Homma and Yakiyama (1988) and Zhou (1999). The heat loss increased as the air velocity increased from 0.6 m/s to 1.5 m/s . As expected the increase of air velocity had higher impact at the face with no any perception at the lower body parts, as shown in Figure 3(3a and 3b) when the room temperature was 26°C . Besides, the cooling effect was higher at 26°C than at 28°C and 30°C , which is shown by the body part heat loss in Figure 4. Whole body temperature only decreased 1 K by 1.5 m/s while head temperature decreased 3.6 K .

Table 2: Whole body and head region T_{eq} s and heat losses at different room temperature and constant air velocity

	t_a ($^\circ\text{C}$)	Equivalent temperature ($^\circ\text{C}$)			Heat loss (W/m^2)		
		26	28	30	26	28	30
whole body	no fan	24.9	27.8	29.7	47.3	35.1	27.5
	0.6 m/s	24.7	27.5	29.2	48.2	36.6	29.6
	1 m/s	24.3	26.9	29	49.7	39.1	30.3
	1.5 m/s	-	26.5	28.8	-	40.4	31.3
head	no fan	23.9	26.6	28.7	45.5	35.6	28.1
	0.6 m/s	21.4	24.5	26.7	54.6	43.2	35.4
	1 m/s	19.6	22.7	25.9	61.2	49.7	38.1
	1.5 m/s	-	21.6	25.1	-	53.8	41.1

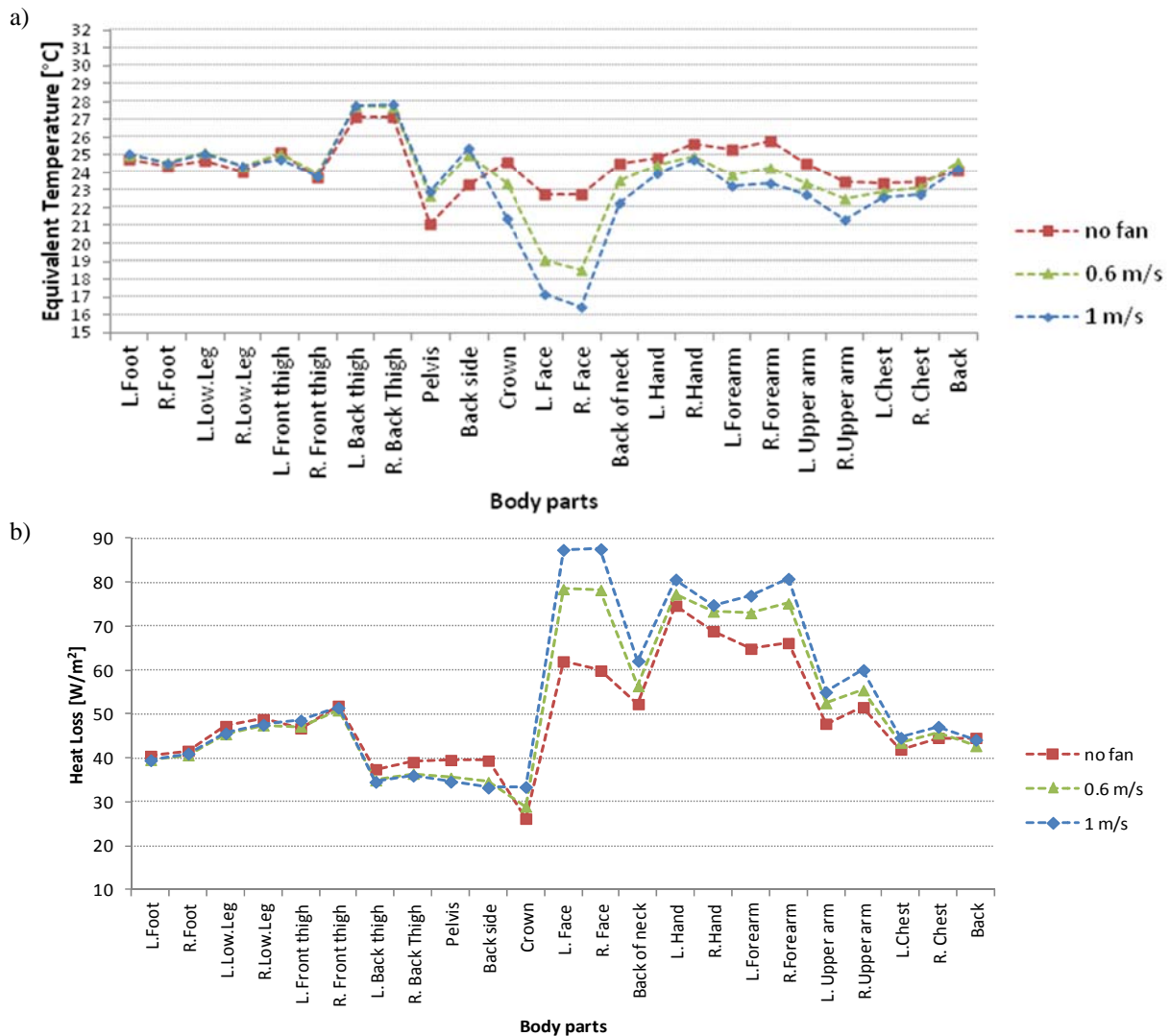


Figure 3: Equivalent Temperature (T_{eq}) and body parts Heat Losses at 26°C exposure and different air velocities

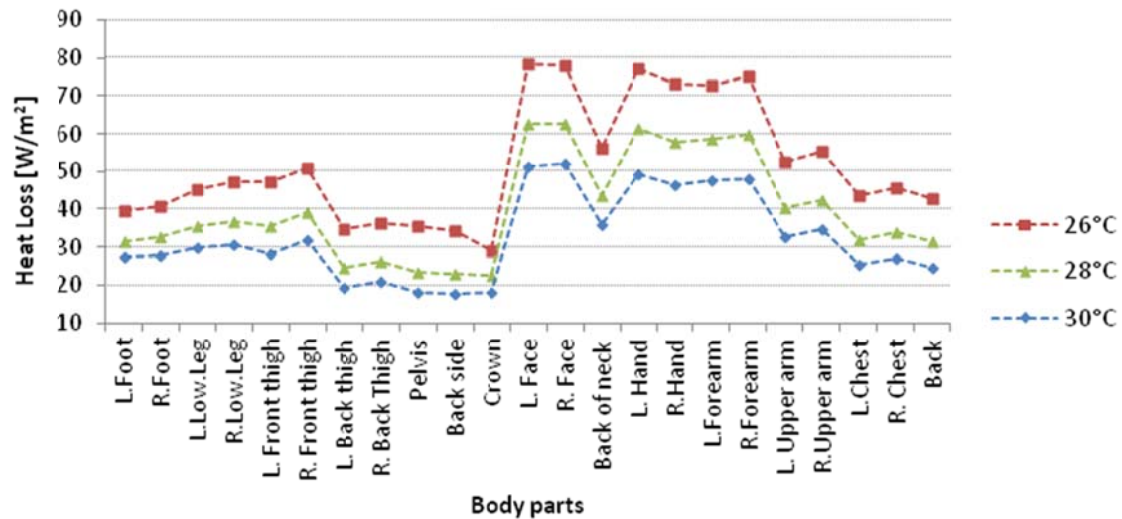


Figure 4: Body parts heat losses at 26 °C, 28°C, and 30 °C room temperature and 0.6 m/s of constant air velocity

The measurements performed with the thermal manikin show that the cooling effect decreases with the increase of the environmental temperature, and it increased with the increase of the constant air velocity resulting in higher head heat losses.

Following the experiments with thermal manikins, the human subjects' experiments were performed to evaluate which are the right combination of air temperature and constant air velocity that can provide thermal comfort and no draught problems.

Previous studies, as shown in Figure 5, reported preferred air velocity to offset warm environments higher than 0.18 m/s suggested by ISO Standards 7730 (2005) for building category B. In Figure 5 are reported the preferred air velocities obtained, at almost the same experimental set up, for the Scandinavian human subjects' experiment of Cattarin et al. (2012) and the present study.

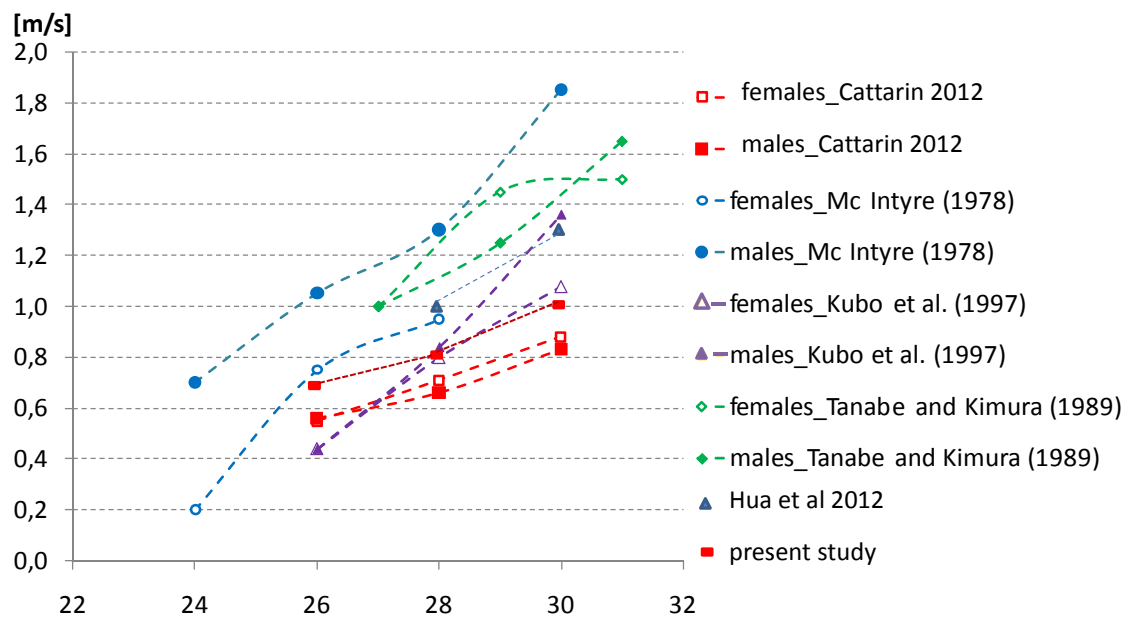


Figure 5: Preferred Air Velocities from Human Subjects Experiments

The two human subjects' experiments, having 32 and 27 Scandinavian participants (in Cattarin et al. 2012 and in the present study) present slightly different results. This could be

due to the different type of fan used, where later a larger diameter and the possibility to provide higher air velocity (>1.2 m/s). As reported in Table 3, the results of the 2nd experiments had on average circa 0.1 m/s higher preferred air velocity and higher percentage of dissatisfaction (PD). However, only at environmental temperatures of 26 °C and 28 °C the higher air velocity helped to offset the warm sensation by achieving neutral thermal conditions ($TSV < \pm 0.5$) and low dissatisfaction (PD) as reported in Table 3 and shown in Figure 5. The local air velocity decreased the subjective thermal sensation (TSV) of one step in the evaluation scale of thermal comfort, while the estimated thermal comfort through the measured equivalent temperature ($PMV_{T_{eq}}$) resulted closer to neutral. However, at temperatures higher than 28 °C, the preferred local air movement was not enough to fulfil the occupants cooling needs as the environment was assessed warm and additional physiological complains, like eye dryness and nose irritation, were expressed through the questionnaires.

Table 3: Scandinavian Human Subjects Results

t_a (°C)	1 st experiment (Cattarin et al., 2012)			2 nd experiment		
	v_a (m/s)	TSV (-)	PD (%)	v_a (m/s)	TSV (-)	PD (%)
26	0.56	0.0	4	0.70	-0.1	19
28	0.69	0.5	10	0.82	0.3	12
30	0.85	1.3	55	1.03	0.9	35
32	-	-	-	1.5	1.2	49
34	-	-	-	1.7	1.6	63

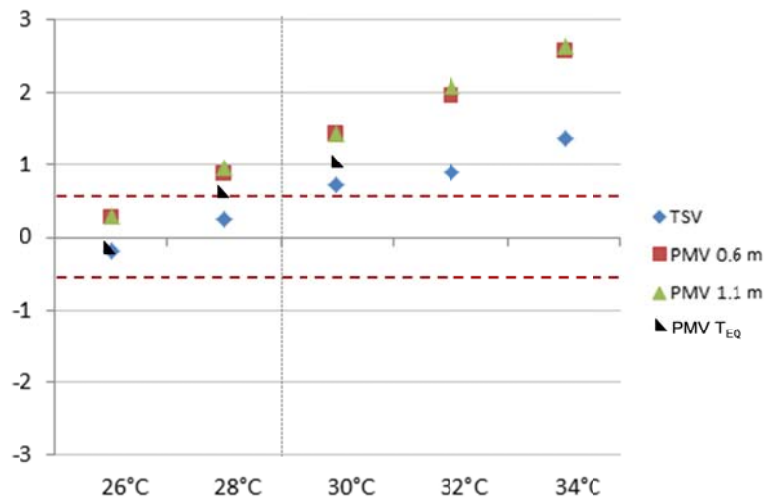


Figure 6: Evaluation (TSV) and Estimation (PMV) of Studied Thermal Comfort Environments

Comparing the present results of preferred local air velocities with the one obtained in a subjects experiment conducted with Chinese population (Zhou et al. 2006) it appear clear the different preference with higher air velocity and capability to adapt and achieve comfortable conditions, even at 30 °C, from the Chinese population.

Even if the Scandinavians appeared keen to higher air velocities to offset warm environments, they showed lower capability of adaptation maybe due to their daily exposure to colder environments.

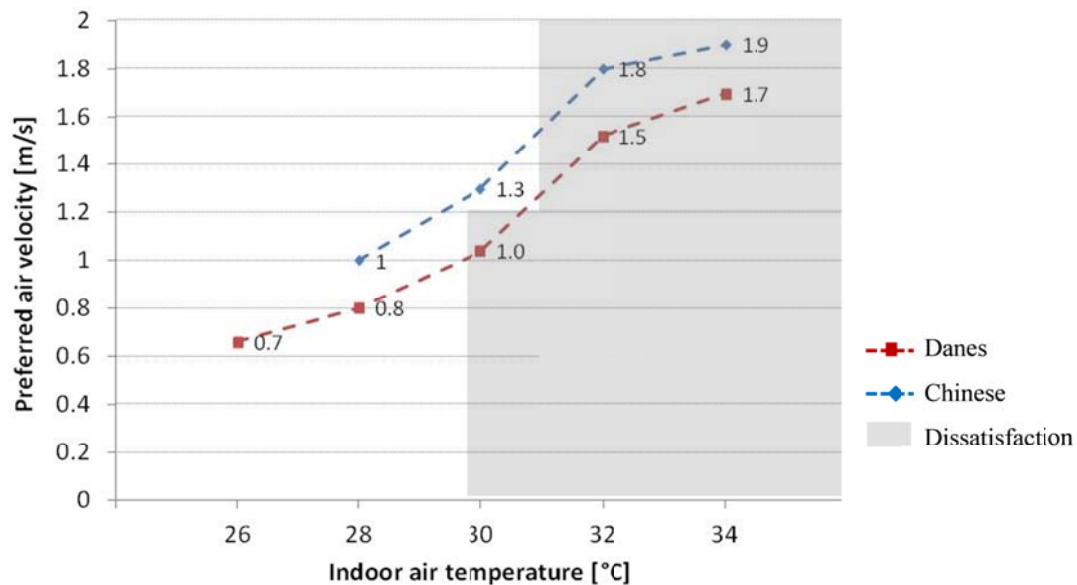


Figure 7: Subjective preference of local air velocity and comparison between Danish and Chinese participants

4 CONCLUSIONS

In this study the occupants, at sedentary positions, were exposed to an increased room temperature and local front air movement provided by a desk fan.

Higher local air velocity compensates higher room temperature at 28 °C and °30 C, resulting in neutral thermal environment.

Significant individual difference in the preferred air velocities was found which indicates that people differ and that personal control is important.

Comparing the present study with Danes and the one with Chinese subjects under similar experimental conditions, it shows acceptability and preferences in terms of neutral thermal environment.

5 ACKNOWLEDGEMENTS

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